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ECL 242

THE GALLOPING GRAIN GRINDER

A large segment of a welded blower fan assembly on an operating grain and feed mill flew off and killed the owner. This case follows the investigation into why the blower failed.

Written by C. O. Smith, College of Engineering and Technology, University of Nebraska, Omaha, Nebraska.

Appreciation is expressed to Mr. Eugene Field, Esq. of Kalamazoo, Michigan for extending the courtesy of his files to use in writing this engineering case.

THE GALLOPING GRAIN GRINDER

PART A

The Circumstances

Late in October 1965, Mr. Green, a farmer, bought a new grain and feed mill for grinding or chopping grain, silage, etc. This is portable equipment powered by a take-off unit from a tractor. Grinding is accomplished by hammers which are sheet type blades with a hole in one end. Twenty-two hammers (with spacers between) are slipped on each of three hammer shafts which, in turn, are mounted through the apices of an equilateral triangle (cut from plate) at each end of the shafts. (See Exhibit A1) The whole assembly is keyed to a cylinder shaft. Grain or silage is put into a hopper at the drive end of the mill and moved toward the exit by a screw conveyer. At the exit end, a blower fan assembly blows the ground material through a tangential outlet into a bin or other container. (See Exhibit A2)

On 27 March 1970, the mill was repaired. A receipted bill showed replacement of a cylinder shaft, main bearings, pulley and tapered key. There was some question as to whether or not the blower fan assembly was replaced. Toward the end of June 1970, the mill plugged. Examination showed that the fan assembly had separated between the hub and the rest of the assembly. A new blower fan assembly was installed on 26 June 1970.

The mill was used once a week through the summer for a maximum of two hours each time. The mill had been in use for 30 to 60 minutes on the first of September 1970, when the blower fan assembly failed. One piece passed through the sheet steel shroud surrounding the blower fan, hit Mr. Green, and fatally injured him. Mrs. Green filed suit against the manufacturer (Breeze Manufacturing Co.).

Observations and Data

The blower fan assembly which killed Mr. Green is shown in Photographs A1 and A2. The blower fan assembly consists of a cylindrical hub, a spider (flat, hexagonal plate with a central hole), six angle iron arms attached to the spider, with 2 bolts per arm, and six fan plates. One fan plate is attached to each arm by three rivets. During assembly, the spider is slipped over the hub with the two pieces then being welded together on an automatic submerged arc machine using solid wire electrode (3.1 mm: 1/8 in) at about 400 amps and 35-40 volts. The weld is on only one side of the spider.

The service manual for the feed mill indicates the rotational speed should neither exceed 2600 rpm nor drop below 2200 rpm. It further indicates that, for best results, the power take-off speed should be 540 rpm under load. The tractor used to power the mill had a power take-off speed of 548 rpm at an engine speed of 1400 rpm, independent of which gear was being used. A section of the fracture surface on the detached segment of the blower

spider is shown in Photograph A3. This is between blower arms 5 and 6 (See Photos. A1 and A2). The "matching" fracture surface on the portion of the blower spider still attached to the hub is shown in Photograph A4.

The assembly which was removed from the mill in June 1970 was examined. The spider and hub had completely separated in the weld between the two pieces. Visual examination with a hand magnifying glass indicated some porosity in the weld.

Questions:

1. What, in your opinion, is the cause of the failure of the blower fan assembly which killed Mr. Green?

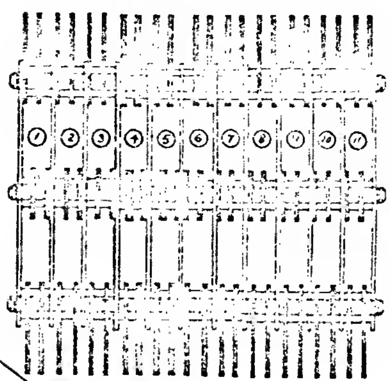
2. If you can not form an opinion, what additional investigation would you perform to enable you to form an opinion?

Mill Cylinder

EXHIBIT A1

page 33
Service Manual

HAMMER ARRANGEMENT

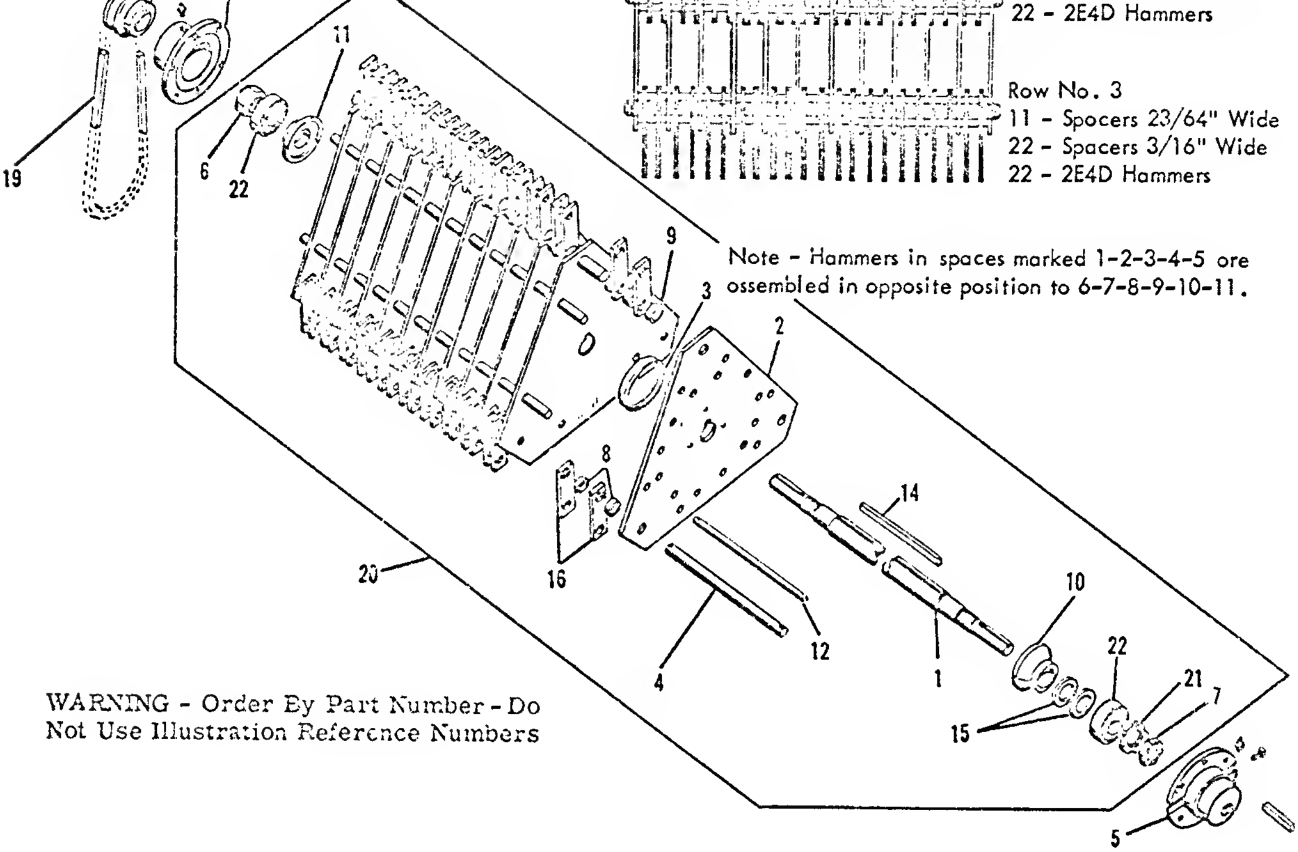


Row No. 1
22 - Spacers 23/64" Wide
22 - 2E4D Hammers

Row No. 2
22 - Spacers 23/64" Wide
22 - 2E4D Hammers

Row No. 3
11 - Spacers 23/64" Wide
22 - Spacers 3/16" Wide
22 - 2E4D Hammers

Note - Hammers in spaces marked 1-2-3-4-5 are assembled in opposite position to 6-7-8-9-10-11.



WARNING - Order By Part Number - Do Not Use Illustration Reference Numbers

Ref. No.	Part No.	Part Name	No. Req.
1	2E1J	Cylinder Shaft 2 x 32-9/16 . . .	1
		Tapered Key 3/8 x 2-1/2 . . .	1
2	2H2B	Cylinder Plate	12
3	2H3B	Cylinder Plate Spacer (2H3-1).	11
4	2E5	Hammer Shaft 5/8 x 14-1/16 . .	3
		Cotter Pin 3/16 x 1-1/4	6
5	1H5D	Cylinder Bearing Housing - Right	1
		Grease Fitting 570012 (1684B)	1
		Sq. Hd. Set Screw 5/16 x 1-1/4	2
6	2H6D	Cylinder Shaft Nut - Left	1
		Soc. Hd. Set Screw 1/4 x 3/8 . .	1
7	2H6E	Cylinder Shaft Nut - Right . . .	1
8	2E12A	Hammer Spacer	22
9	2E13A	Hammer Spacer	55
10	2E18B	Cylinder Collar - Right	1

Ref. No.	Part No.	Part Name	No. Req.
11	2E19C	Cylinder Collar - Left	1
12	2E20	Hammer Stop 5/16 x 13-7/8 . .	6
		Cotter Pin 1/8 x 3/4	12
13	2H22S	Conveyor Drive Sheave	1
		Soc. Hd. Set Screw 5/16 x 3/8 .	1
14	2E31A	Cylinder Key 1/4 x 3/8 x 11-1/2	1
15	2E33	Shim Washer	2
16	2E34	Hammer (66-2E4D)	1 Set
17	1H48J	Cylinder Bearing Housing - Left	1
		Grease Fitting 570002 (1610B)	1
18	13E60	Main Shaft Key	1
19	5H75	Conveyor Drive Belt	1
20	1E100	Cylinder Assembled	1
21	520002	Lock Washer (W-10)	1
22	520117	Bearing (8510-XR1B)	2

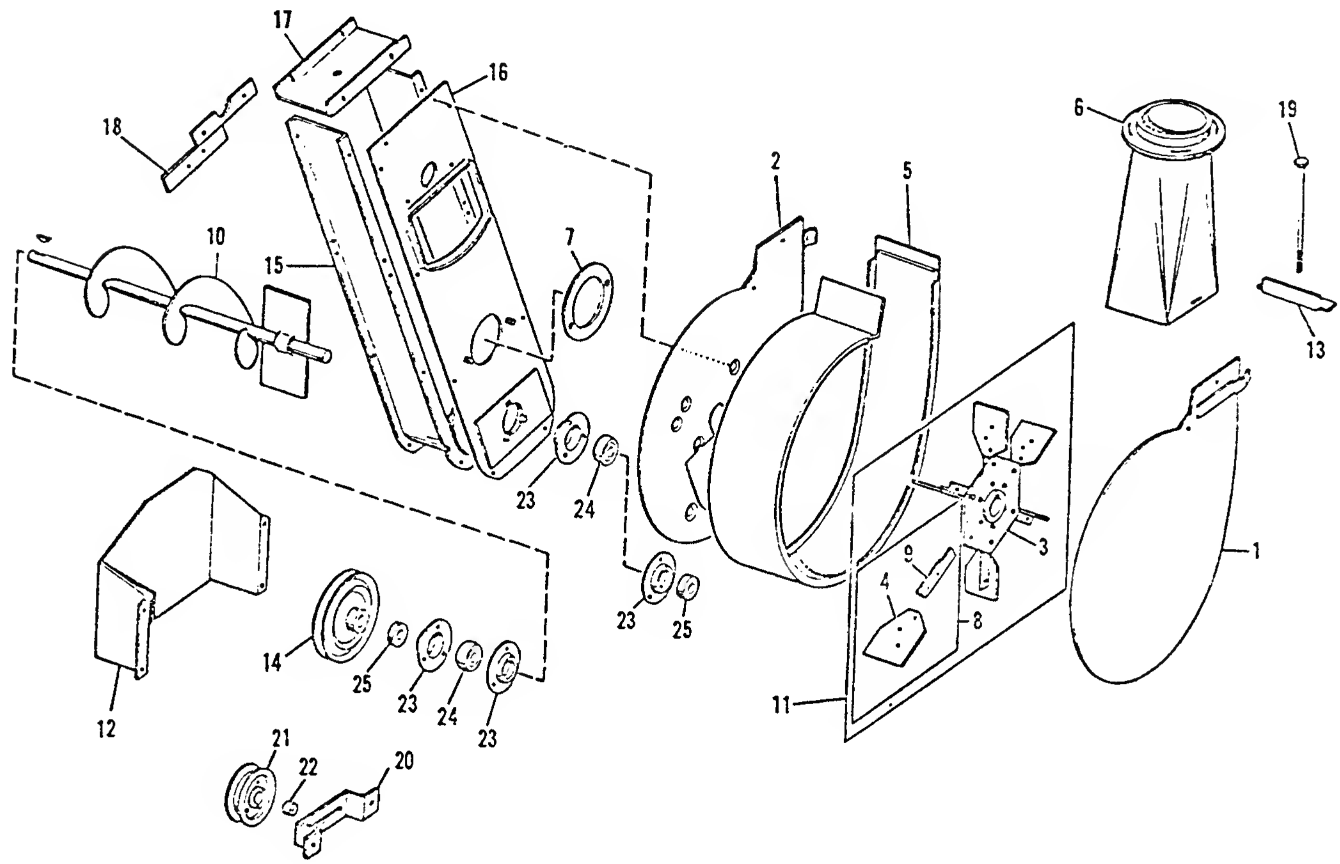
ALWAYS GIVE MODEL AND SERIAL NUMBER WHEN ORDERING SERVICE PARTS

Mill Conveyor and Blower

EXHIBIT A2

page 34
Service Manual

WARNING - Order By Part Number - Do Not Use Illustration Reference Numbers



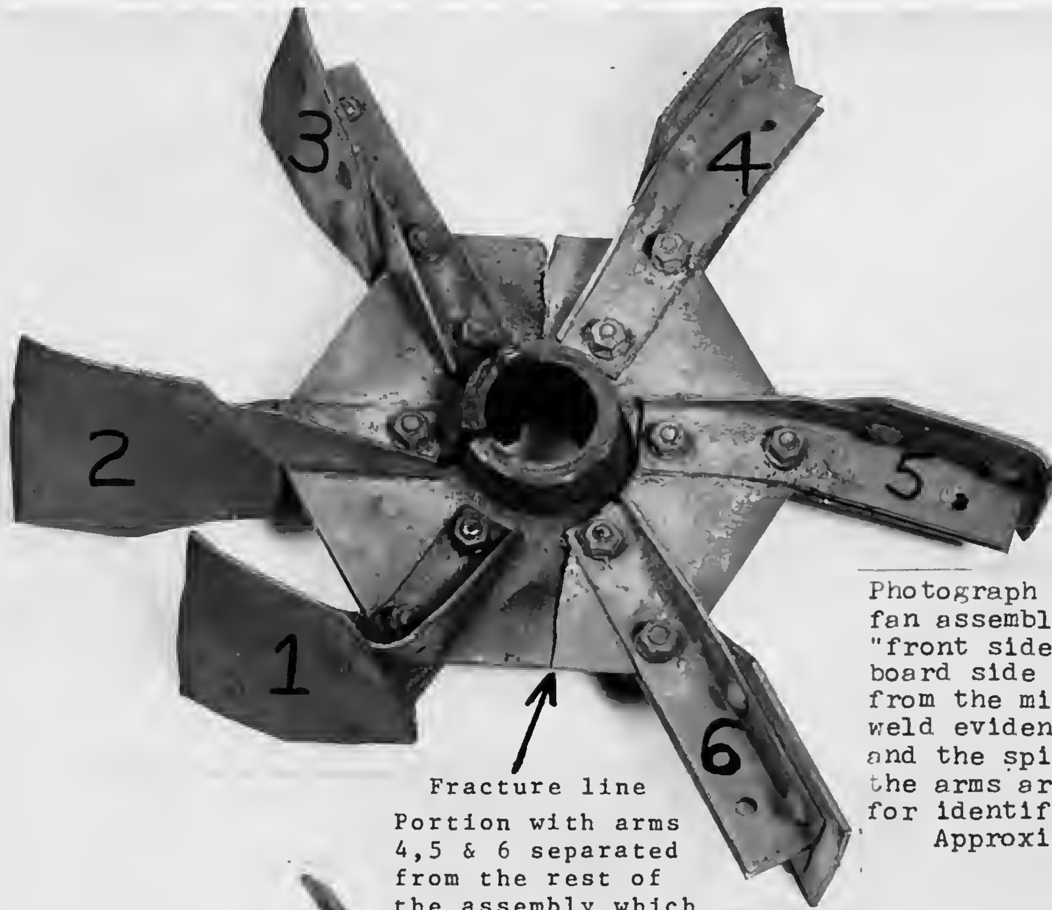
Ref. No.	Part No.	Part Name	No. Req.
1	5H1E	Blower Side - Right	1
2	5H2H	Blower Side - Left	1
3	5H3G	Blower Spider	1
4	5H10E	Fan Plate	6
		Round Head Rivet 5/16 x 1/2 .	18
5	5H11B	Blower Rim	1
6	5H12E	Blower Outlet	1
7	5H20A	Inspection Hole Cover	1
8	5H23C	Blower Arm Assembled	6
9	5H43B	Blower Arm	6
10	5E52A	Conveyor	1
		Woodruff Key 1/4 x 1	1
11	5H56G	Blower Fan Assembled	1
		Sq. Hd. Set Screw 1/2 x 3/4 ..	1
12	5E62	Conveyor Drive Guard......	1
13	5H63	Blower Rim Tightener	1
14	5E68	Conveyor Sheave	1
15	5H71	Blower Inlet Rim	1
16	5H71B	Blower Inlet Cover.........	1
17	5H72	Blower Inlet End Cover.....	1
18	5H73	Blower Inlet Deflector	1
19	5H74	Rim Tightener............	1
20	5E76	Belt Tightener Bracket	1
21	5E77	Belt Tightener Pulley	1
22	6H130	Tightener Pulley Spacer	1
23	H275	Bearing Retainer	4
24	520063	Ball Bearing (RA100NPPB) ..	2
25	520084	Bearing Collar (S1100K)	2

ALWAYS GIVE MODEL AND SERIAL NUMBER WHEN ORDERING SERVICE PARTS

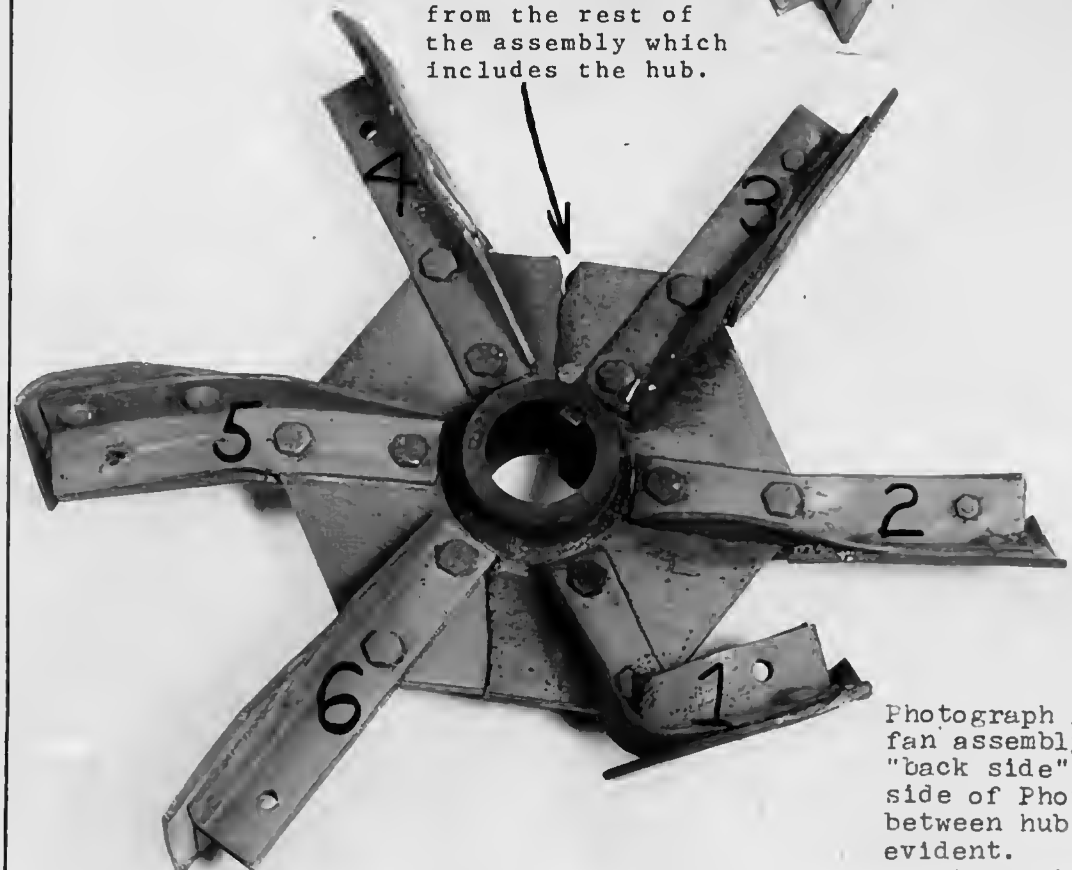
Cylinder shaft (#1, Exhibit A1) is driven by an external source of power, e.g., power takeoff (PTO) shaft of a tractor, at the left end (Exhibit A1). Cylinder shaft rotates the hammer arrangement which grinds the grain. Cylinder shaft also drives the conveyer (#13 & 19, Exhibit A1) and (#14, Exhibit A2). Pulverized grain passes through a sieve to the lower compartment where it is transferred by the conveyer (#10, Exhibit A2). The blower assembly (#11, Exhibit A2) is keyed to the conveyer.

Exhibit A3

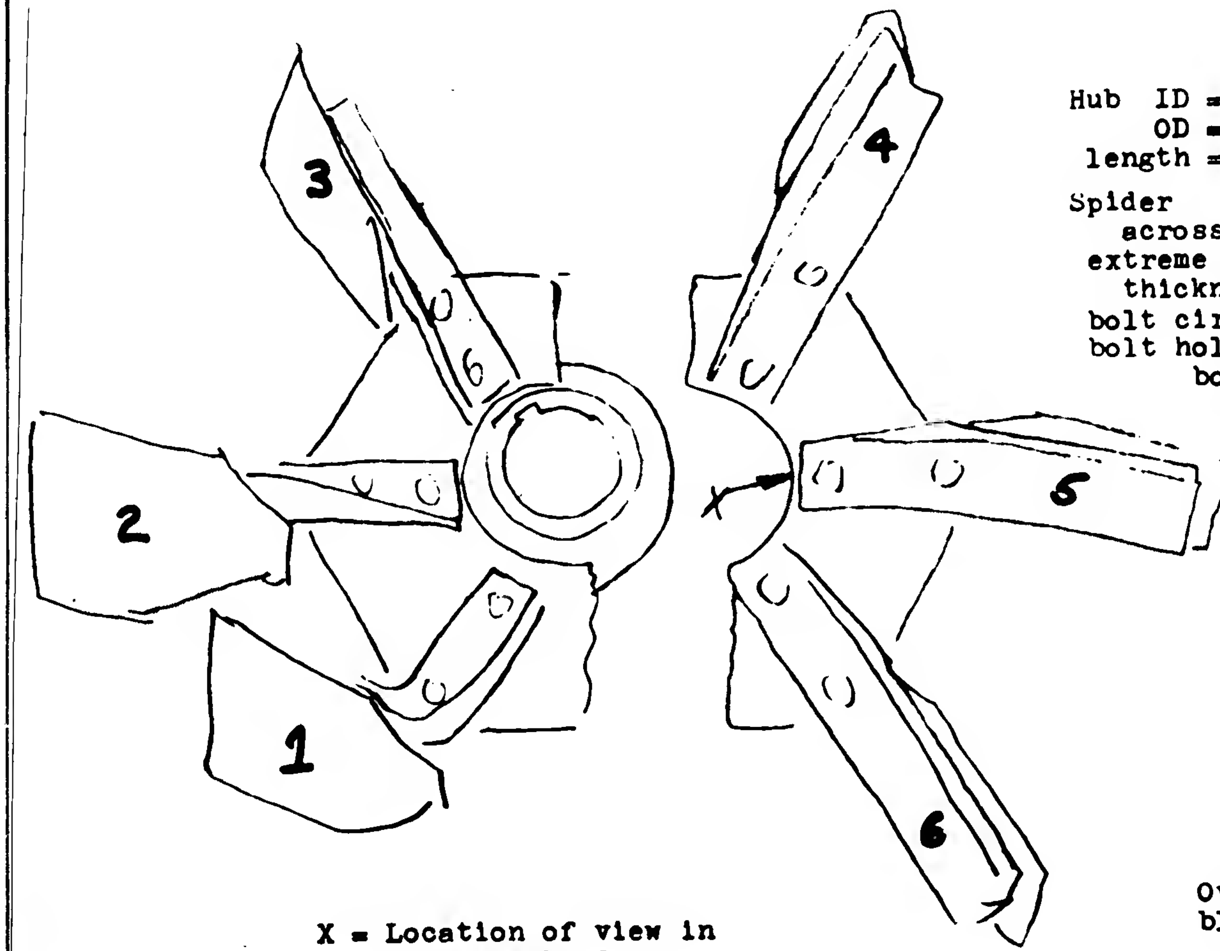
Comments on Grain Mill Arrangement



Photograph A1 - Failed blower fan assembly viewed from "front side", i.e., the outboard side or the side away from the mill. There is no weld evident between the hub and the spider. Numbers on the arms are arbitrary and for identification only.
Approximately 1/3 X



Photograph A2 - Failed blower fan assembly viewed from "back side", i.e., reverse side of Photo. A1. Weld between hub and spider is evident.
Approximately 1/3 X



Hub ID = 1 7/8 in
OD = 2 5/8 in
length = 2 1/2 in

Spider
across hex = 8 in
extreme points = 9 1/4 in
thickness = 1/4 in
bolt circles = 4 & 8 in
bolt holes = 9/16 in D
bolts = 1/2 in D

Fan plate
3 3/4 x 4 5/8 x 3/16 in

Fan arm (angle)
2 x 1 1/4 x 1/8 x 6 5/8 in long

Rivets 5/16 in D

Arm assembly (plate, arm, rivets)
1 lb, 14 oz
cg 5 5/8 in from CL

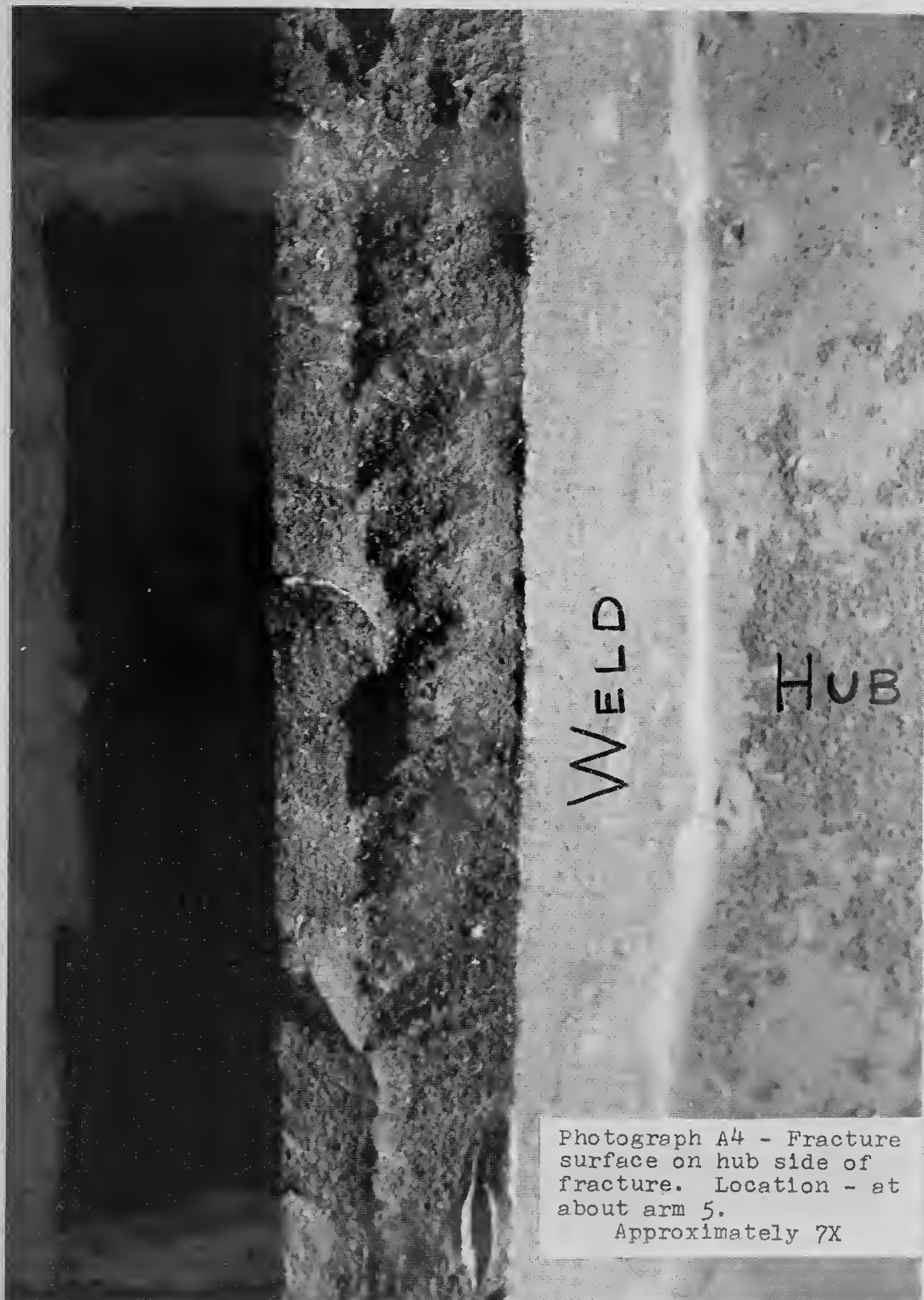
Overall diameter of blower assembly
18 in

X = Location of view in Photograph A3

Exhibit A4

View of fan assembly broken in two pieces

Photograph A3 - Fracture surface on spider side of fracture. Location - between arms 5 and 6. Approximately 8X



Photograph A4 - Fracture surface on hub side of fracture. Location - at about arm 5.
Approximately 7X

THE GALLOPING GRAIN GRINDER

PART B

Plaintiff's Expert

Mr. McGowan, a registered professional engineer (mechanical and metallurgical) was retained by plaintiff's counsel and made the following report:

1. The blower fan assembly in question has been examined in considerable detail. The probable stress in the assembly has been estimated. Assuming a balanced assembly running at 2400 rpm and conservative assumptions (meaning worst case extremes), the radial and tangential stresses at the hub are calculated to be less than 813 and 24.1 MPa (1200 and 3500 psi), respectively.

2. The spider plate was analyzed by spectrographic and wet chemical procedures and found to be within the specifications for AISI 1020 steel. The hub and weld bead were analyzed spectrographically and also appear to be AISI 1020. Even though this steel is a relatively low strength alloy, it would be expected to withstand much higher stresses than those calculated above in item 1. The choice of this alloy for this application is reasonable. The grain size of the plate is somewhat smaller than that of the hub but both appear to be reasonably small and acceptable for this application.

3. Examination of the fracture surface indicates that the last portion of the spider plate to fail is the section between blower arms 3 and 4 (numbering of arms is completely arbitrary). The appearance of the entire fracture surface indicates a high probability that fracture initiated in the section along the hub between arms 5 and 6.

4. A magnetic dye penetrant inspection was performed on the hub and attached segment of the spider. Clear evidence of a crack at the "line" of junction between the weld and spider plate (see right side of Photograph A2) was found. This crack extended completely around the periphery with the exception of one short distance. In addition, there is a crack in the weld bead near arm 1.

5. Radial cuts were made between arms 5 and 6 and at arm 2. A view of the cut close to arm 2 (See photograph A1 for location) is shown in Photograph B1. A crack is obvious at the point where the weld bead and the plate join (the crack discussed in item 4). A second crack is seen in the weld bead. This crack initiates at the end of the space or gap between spider plate and hub. A geometrical condition such as this creates a stress concentration which may cause the actual stress to be several times the nominal stress calculated by standard formulas. In the context of this specific blower fan assembly, this is a design (or manufacturing) defect which could have been avoided by welding on both sides of the joint rather than just

Since failure occurred in the spider, with a crack running essentially across a diameter and around the welded hub, I have concentrated the analysis on that area. At 2700 rpm this analysis predicts a tensile stress of 6680 psi while at 4000 rpm a tensile stress of 18,500 psi is predicted. These stresses are well below the yield point for steel (hot rolled plate is above 30,000 psi). It is my opinion that the design is adequate for rotation at 2700 rpm with sufficient safety factor to allow operation in excess of 4000 rpm for short periods. However, at higher speeds, the stress levels are such that when combined with vibratory loads the endurance limit could be exceeded.

An examination of a photograph showing the failed spider indicates the crack did not propagate through the bolt holes but probably originated in the stress concentration around the hub weld. This failure was probably initiated by either a. overload due to over-speeding or jamming of the blades, or b. fatigue from vibration and overloads. The crack pattern is a classic one and I could probably tell you more after examining the actual pieces.

Further Investigation

A meeting was held at the Green farm on 4 June 1973. Those attending were plaintiff's attorney, attorney for Breeze, Mr. Mack and Mr. Huff (director of engineering for Breeze). The mill was operated without a fan blower assembly. Mr. Huff had a number of comments:

It was his opinion that there should be no problem with the mill running at over 3000 rpm if everything were in good condition. He noted that the mill vibrated excessively at both 540 (design value) and 720 rpm power takeoff speed.

Mr. Huff knew of only one instance (in over 50,000 similar mills) where a blower fan assembly broke. In that case, the fan hooked on the shroud and even then, only the fan plates came off. It was his offhand opinion that the blower fan in question broke because of fatigue due to vibration and not because of a defective weld.

Welding between the spider and hub was done in one pass. Welding was on one side only because Breeze felt that was all that was necessary. There was periodic inspection to be sure that the weld was the correct size and had adequate penetration.

Mr. Huff tried to determine if there were end-play in the bearings or if the shaft were loose in any way. He could not find end-play but believed that might have been since everything was rusted tight. He did not believe that the rust which accumulated after the accident caused the mill to vibrate more than it did when previously used.

the one side. Since the weld appears to have been a single pass weld, it would not have been very difficult to have made a similar single pass weld on the other side of the joint.

It is obvious that the first crack mentioned above starts at the junction of the weld bead and the spider plate. From Photograph B1 it appears that there is a more abrupt change in grain size along this junction than along the junction between the weld bead and the hub.

6. A second radial cut was made between arms 5 and 6. Small sections along this cut on both sides of the fracture surface (which thus appeared in profile) were mounted for metallographic examination.

These specimens were examined under an optical microscope at 100 diameters magnification. A small crack initiating at the gap between the plate and hub was observed. The fracture appears to have started at the junction between the weld bead and the spider plate. There are also two secondary cracks in the plate, one in the section closer to the hub and the other starting at about the same place but extending outward (in the radial sense). The transition in grain structure is more abrupt between the weld bead and plate than between the weld bead and hub. At the same time, it should be noted that the grain structure observed is not particularly abnormal.

It appears that the fracture started someplace in the general vicinity between arms 5 and 6 and propagated circumferentially around the hub with the last portion to fail being located between arms 3 and 4.

Conclusions:

1. There is a design (or manufacturing) defect in this blower fan assembly. This defect is the gap which is left between the spider plate and hub after joining the two by welding. This will ultimately lead to failure even if there are no other faults or defects.

2. There is a manufacturing defect related to the weld between the spider plate and the hub which has caused formation of extensive cracking (most of the periphery of the weld) on the surface of the spider plate at the junction between the weld bead and the spider plate.

10 April 1973

Defense Expert

Mr. Mack, an engineering professor at a university, was retained as an expert by the attorney for Breeze Manufacturing Company. On 8 January 1973, Mr. Mack wrote the defense attorney a letter, of which a part said:

Mr. Huff admitted that he had seen as much vibration at the end of the test line but there was no breakage then since such a mill was run for only a short time. Vibration in such a case was due to bad bearings or an unbalanced cylinder.

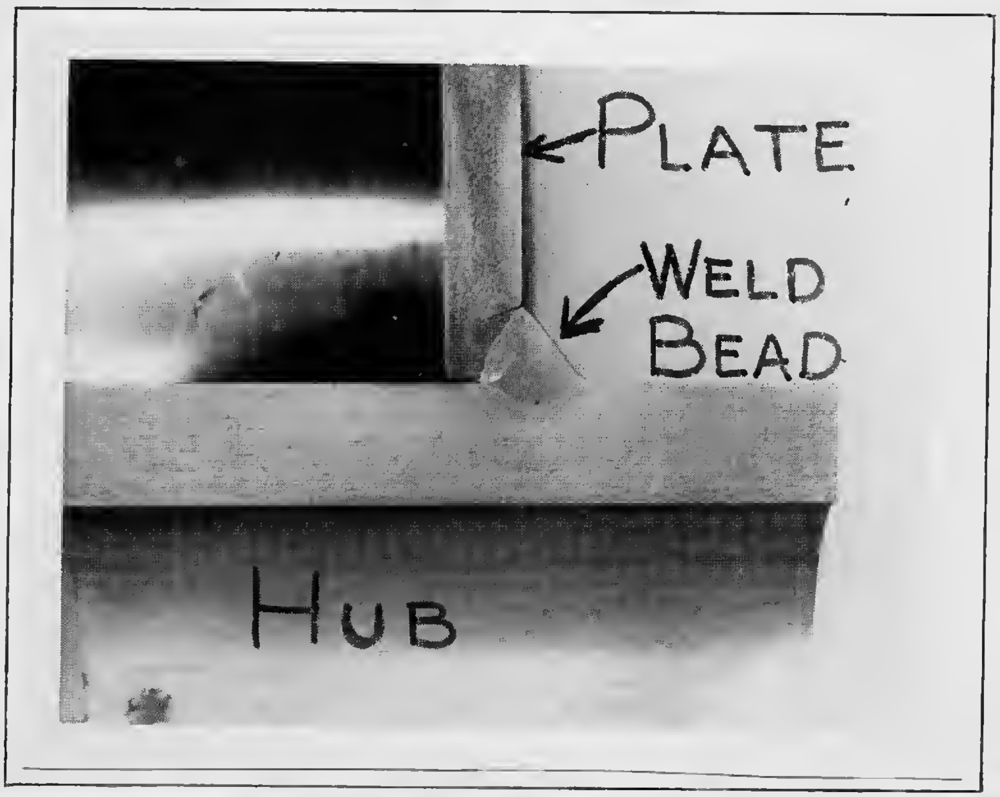
To summarize, Mr. Huff said the excessive vibration could be from improper assembly of the hammer mills, defective bearings or a defective main shaft. Metal fatigue was the most probable cause of fracture of the spider, although a defective weld might cause the fracture. Operation of the mill with the amount of vibration observed would cause parts to fatigue and cause excessive wear.

Questions:

1. Now that you have more information, have you an opinion about the cause of the failure of the blower fan assembly?

2. If you do, what changes in design and/or manufacture would you make to eliminate (or minimize) the possibility of similar failures?

3. If you do not yet have a firm opinion, what additional information do you need?



Photograph B1 -- Section of hub, weld bead, and spider from failed fan assembly. There are two obvious cracks: one starting at the edge of the weld and the other starting at the gap between hub and spider.
Polished and etched with 2% Nital. Approx. 1½ X

THE GALLOPING GRAIN GRINDER

PART C

Defense Expert

As a result of the meeting at the Green farm on 4 June 1973, Mr. Mack wrote the following report:

The subject machine was examined by Dr. Mack, June 4, 1973. At that time the machine was operated without a blower and significant vibrations in the hammer mill assembly were noted. It was then decided to remove the hammer mill to Dr. Mack's laboratory and carefully disassemble it to check the balance and mechanical condition. This was accomplished the week of June 9, 1973.

This examination revealed that:

1. All hammers and spacers were in place.
2. 2E20 hammer stop row 1A Drive end broken off at cotter pin hole, fan end cotter pin (too small).
3. 2E20 hammer stop row 1B Blower end cotter pin has both ends broken off.
4. 2E20 hammer stop row 2A drive end cotter pin has both ends broken off.
5. 2E20 hammer stop row 2B Fan end cotter pin has one end broken off.
6. 2E20 hammer stop row 3A Fan end cotter pin completely broken off.
7. 2E20 hammer stop Row 3A Drive End cotter pin (too small) one end broken.
8. 2E20 hammer stop row 3B Fan End cotter pin (too small).
9. 2E20 hammer stop row 3B Drive end cotter pin missing.
10. 2E5 hammer shaft Row 1 Fan end cotter pin completely broken off.
11. 2E5 hammer shaft Row 1 Drive end cotter pin missing.
12. 2E1J cylinder shaft under size, shows extreme wear! 1.792 OD
13. 520117 bearing (NDH # 8510 - XRIB) drive end shield has damage not severe; inner race shows some wear (ID 1.971) (OD 3.542)
Note: NDH Bearing Specs. from Detroit Ball Bearing

    ID 1.968

    OD 3.543

    Inner Race Width 1.024

    Outer Race Width .866

14. 2H6D cylinder shaft nut left shows extreme wear!

Conclusions

The inboard or drive end bearing showed wear on the inner race surface and evidence of over heating. The shaft surface upon which the bearing is seated showed extreme wear, and a clearance of 0.179 inches on the diameter between the inner race of the bearing and the shaft surface. With this much wear it is amazing that the machine would operate at all. The shaft was worn in other places and showed evidence of long service and maltreatment. The machine should not have been operated in this condition. The severe vibration and resultant stresses would be transmitted to the blower assembly and would cause a rapid fatigue failure.

Mr. Mack is not a metallurgist but did confer with Mr. Burns, a metallurgist. They agreed that the weld was adequate, typical and had good fusion: that the crack appeared at the weakest point; that failure did occur at the weld but the weld was not the cause of failure; and that the shaft had not been replaced. It was their opinion that the inner bearing was simply not worn enough to indicate that a new shaft and bearing had been installed at the same time (March 1970).

In addition, they argued that of 50,000 Breeze mills placed in the market, only the Green mill failed and not only once, but twice. Common sense indicates something wrong with the Green mill and not other mills. That problem was probably bearing freeze-ups and/or poor maintenance leading to a badly worn shaft. They claim that negligence of Lucky Equipment Sales in failing to replace the shaft as billed, and negligence of Green in operating the mill in such a vibratory condition led to the fractures of the weld and spider.

Plaintiff's Attorney

As a consequence of these findings, the plaintiff's attorney filed suit against Lucky Equipment Sales, claiming negligence in failure to replace the shaft, or, if it had replaced the shaft, negligence in re-installation so as to cause a highly abnormal amount of wear.

Lucky Equipment Sales

Lucky responded by saying that it had possession of the shaft which was removed in March 1970.

The shaft taken from the mill on 4 June 1973 and that alleged by Lucky Equipment Sales to have been taken from the mill in March 1970 were compared. The two were substantially the same and clearly were "identical" parts. The inboard bearing sites of the two are compared with Photograph C1 of the shaft (shaft A) produced by Lucky Equipment Sales and Photograph C2 of the shaft (shaft B) taken from the mill on 4 June 1973.

Defense Expert

Mr. Burns wrote a report after the comparison in which he suggested three possibilities:

1. Shaft A was worn by an inoperative bearing. The shaft was replaced with shaft B and new bearings. The new bearing froze up and produced the damages shown by photograph C2. This in turn caused the fractures of the two blower fans.

However, if the above be true, a faulty inboard bearing assembly would be evident.

2. Again, Shaft A is worn and replaced by Shaft B but new bearings are not installed with new shaft. This causes shaft B to wear rapidly.

If true, a faulty inboard bearing assembly would be evident.

3. There was no Shaft A. Only Shaft B existed as the original and sole shaft worn by a frozen bearing. During repairs, only new bearings were replaced, and not a new shaft as claimed by Lucky Equipment Sales.

Plaintiff's Attorney

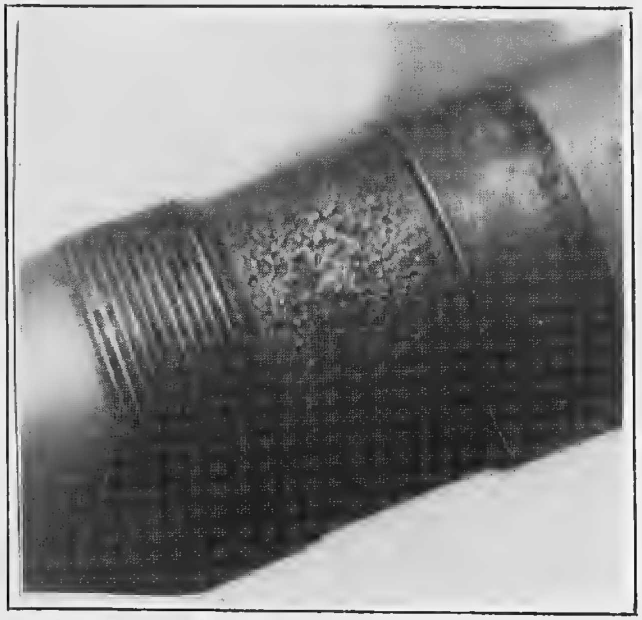
The plaintiff's attorney wrote to McGowan and pointed out that Mack and Burns believed that the bearings must be inoperative for a replaced shaft to be so worn, yet the bearings removed from the Green mill on 4 June 1973 were in tolerance. The attorney asked McGowan what he thought.

Questions:

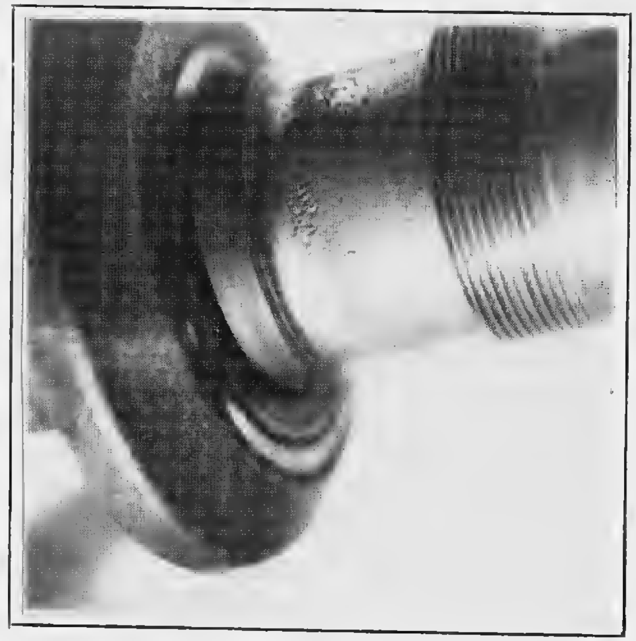
1. What do you think?

2. Do you have an opinion on the cause of the failure?

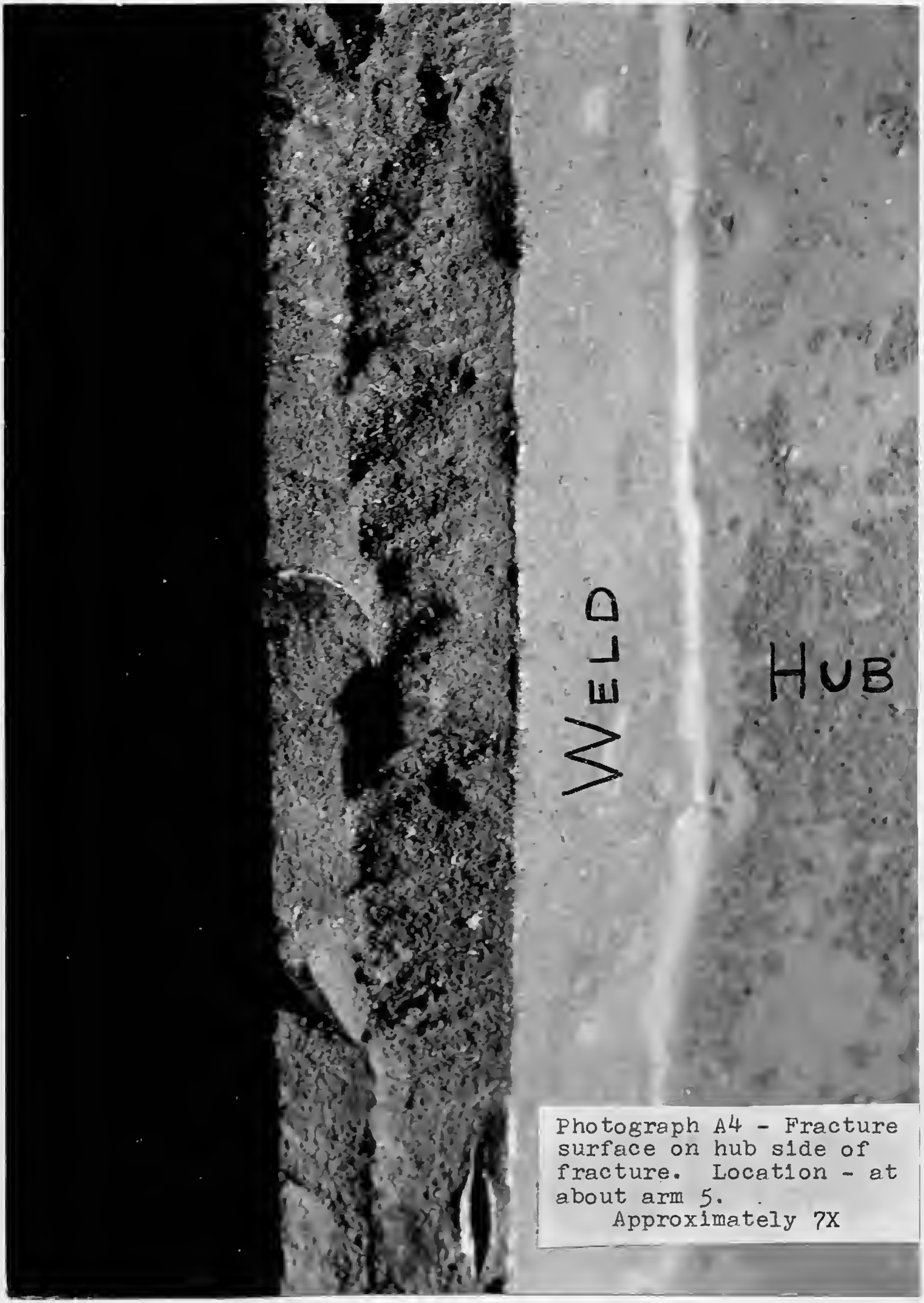
3. How would you handle the situation now?



Photograph C1 -- Portion of cylinder shaft at the bearing at the drive end. Shaft produced by Lucky Equipment Sales and said to have been removed from Breeze mill in March 1970. Wear and pitting of the interface with the bearing is obvious. (Shaft A)
Approximately 3/4 X



Photograph C2 -- Portion of cylinder shaft at the bearing at the drive end. Shaft removed from Breeze mill on 4 June 1973. The shaft diameter is 45.44 mm (1.792 in). Wear and pitting of the interface with the bearing is obvious. (Shaft B)
Approximately 3/4 X



Photograph A4 - Fracture surface on hub side of fracture. Location - at about arm 5.
Approximately 7X

THE GALLOPING GRAIN GRINDER

PART D

Plaintiff's Expert

In response to his client's request, Mr. McGowan replied in part:

I find it difficult to believe that shaft B, with its very limited usage, could have been in the observed condition (after September 1, 1970) if it were replaced on either March 27, 1970 or June 26, 1970.

It would appear that Burns, Mack and I are in agreement that substantial vibration, as was observed in this mill, would lead to premature failure. The major point where we seem to differ is that, in my opinion, the existence of the gap between the hub and spider is a notch which creates a stress concentration and, thus, makes the fan assembly automatically susceptible to failure.

I cannot argue that Breeze has not had 50,000 similar mills function without complaint. I do question the statement to some extent. I grew up on a farm in Massachusetts and was well aware of the lack of "tender loving care" shown toward the equipment which we had. While I have no doubt that many farmers do take excellent care of their equipment, there is no doubt in my mind that a significant number take very little care of their machinery. In my opinion, this is foreseeable and a manufacturer should anticipate this possibility and the possibility that its agents may not always give top quality service.

Resolution

On 20 September 1974, the plaintiff's attorney wrote to Mr. McGowan saying, among other things, "I am pleased to advise that the case has been settled for a modest figure." Most of this was paid by Breeze. This may well be an application of the "deep pocket theory," i.e., the one in the best financial position, is often the one to pay most of the damages to the plaintiff.

Final Comment

Even though Breeze Manufacturing argued that welding on only one side of the hub spider combination was not a design defect, it may be worth noting that shortly after settlement, the production process was modified to weld on both sides and thus eliminate the gap between hub and spider.